An environmentally friendly low-frequency seismic source

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Summary

This is the story of how airguns evolved into an environmentally friendly low-frequency seismic source. It started with a test performed by Veritas DGC that showed the value of low-frequency signal and the failure of conventional airguns to make it commercially viable. It was continued by a few ex-Veritas people at Dolphin Geophysical who saw the promise of a new source and tested a small prototype. Dolphin went bankrupt before it could fund the manufacturing and testing of a full-scale source. That was done by a start-up company, Low Impact Seismic Sources, LISS, that developed the Tuned Pulse Source (TPS™) with funding from Shell. LISS was then acquired by Sercel.

The TPS provides unprecedented performance in low-frequency signal generation, and its environmental impact is much lower than that of any other active seismic source. It is a pneumatic source that operates at lower pressures and with larger volumes compared to other pneumatic sources such as airguns. The TPS evolved from airguns with a few important design features that tune it to release large volumes of air quickly enough to create an oscillating bubble, yet slowly enough to reduce its environmental impact. It is deployed as single sources rather than in arrays. Point sources have significant advantages over arrays. Rather than continue with arrays due to historical reasons, geophysicists can use seismic data processing to, in effect, form arrays from point sources during the actual data processing rather than at the acquisition stage.

Introduction

If you want to predict the future, then you have to invent it. Sixty years ago, Steve Chelminski invented the airgun (Chelminski, 1966). Airguns replaced explosives as seismic sources offshore. The change happened quickly because airguns are safer than explosives and have lower environmental impact. The geophysicists of the time considered the data quality good with explosives. However, they needed a safer source that would match the geophysical quality of explosives. Steve designed the airgun to produce a wave with a short rise time that was as similar as possible to explosives. Rise time is usually defined as the time it takes a source to rise from 10% of its peak Sound Pressure Level (SPL) to 90%. Steve named his invention PAR, an acronym for Pneumatic Acoustic Repeater. Customers wanted to call them air guns because they wanted them to be “like explosives”, and so that is what they did. Later, the name contributed

to the demonization of the airgun. It is now forgotten that airguns replaced explosives just like it is forgotten that the petroleum oil industry replaced the whale oil industry.

For many decades after airguns replaced explosives, offshore seismic inventions concerned mostly the receivers and not the sources. 2D seismic surveys preceded the invention of the airgun. They were conducted with explosives. 3D surveys (Tegland, 1977) started when airguns were mature, reliable technology. Can you imagine acquiring 3D offshore seismic surveys with millions of shots done with explosives?

Progress in receiver technology included first 16-bit recording, then 24-bit. Solid streamers were quieter than kerosene-filled streamers. Higher signal-to-noise ratio (SNR) in seismic acquisition and faster computers enabled more intensive processing, including deghosting. Quieter streamers could be deghosted and deployed deeper and further from the noisy swell on the surface. Slant streamers (Dragoset, 1988) and multi-sensor streamers (Tenghamn and Dhelie, 2009) further improved data quality. Receivers started to be deployed on the seabed (Berg et al., 1994). Wide-azimuth long-offset geometry was natural with ocean bottom nodes (OBN). After the value of wide azimuth was proven with OBN, wide-azimuth towed streamer (WATS) (Threadgold et al., 2006) acquisition was invented.

The above was significant progress with receiver technology, while inventions with sources were more modest. Arrays of many airguns increased the SPL. The diversity of airgun size within arrays improved the peak-to-bubble ratio (PBR), which was considered paramount at the time. Near-field hydrophones started to be used for estimating far-field signatures rather than using statistical gapped deconvolution and modeled signatures. Better understanding of bubble interaction (Ziolkowski et al., 1982) led to clusters (Strandenes et al., 1991). All the while, however, the airguns themselves did not change much. One recent exception was reduced environmental impact (Coste et al., 2014; Tellier et al., 2021). With respect to the geophysics, however, after decades of great progress with receivers and less so with sources, the receivers have not only caught up with the sources but also overtaken them. By the end of the millennium, data quality, and in particular the low-frequency signal, became limited not by the receivers but by the sources.

When I joined Veritas in 2001, the company was acquiring data between the Shetlands and the Faroes to image sub-basalt using new solid streamers and a new source that they named BLAST—acronym for Bloomy Large Array Source Test. Gareth Williams onboarded me and took me through the current R&D projects. He said that if the test was successful, then BLAST would become Bloomy Large Array Source *Technology*. BLAST, designed by Anton Ziolkowski, included airguns with 2000 cubic inch (cui) firing chambers. All other vessels in the Veritas fleet had airguns no larger than 350 cui. I happened to go on the boat that did BLAST, the New Venture, in Aberdeen right after the survey. The 2000 cubic inch guns were already demobilized but the data were still on the onboard processing disks. I had time during a transit to have a good look at the data. I found the low-frequency content impressive, but the gun mechanics told me that they wanted never again to have the 2000 cui airguns on their boat because of safety concerns

and technical downtime. I later followed the data processing at the office and was impressed by the sub-basalt images (Ziolkowski et al., 2003). BLAST was a technical success, but the reluctance of the crew was accepted by management and BLAST never made it from Test to Technology. It was ahead of its time because the airgun technology of the time was not ready for such large volumes of air.

Fast forward to 2014. I joined Dolphin and was working again with Gareth Williams and also with Stuart Denny. Gareth had a proposal from Steve Chelminski who had just invented a new source that he called the Low Pressure Gun (LPG). Steve was again motivated by safety and the environment. The LPG was designed to operate with 600 to 1000 psi. The lower pressure and some deliberate design features reduced its environmental impact and made it safer than airguns. We in Dolphin cared about safety and the environment, but as geophysicists first and foremost, we recalled that what stopped BLAST from becoming a commercial success might not be a problem with the LPG. Moreover, we asked Steve to change the name from LPG to LPS. Source instead of Gun. Dolphin was on the verge of bankruptcy in 2015. Nevertheless, we funded an LPS test in Seneca Lake. Stuart Denny and I went there with Steve and Jan Chelminski. For two days we acquired LPS data. Success! The data were good. The volume of the LPS was up to 600 cubic inches. At 1000 psi it had the same amount of air and the same bubble period as a 300 cubic inch airgun at 2000 psi. So, it matched the airguns of the fleet. But to get to what BLAST had, which was 2000 cubic inches at 2000 psi, the LPS needed 4000 cubic inches at 1000 psi. As it was, the LPS could not do it. We needed a larger source. Steve then designed a larger source and named it TPS for Tuned Pulse Source. Dolphin wanted to fund the manufacturing and testing of the TPS but went bankrupt towards the end of 2015. At the beginning of 2016 I was laid off. I called Steve to give him this bad news and also the good news that I could start a company with him and then get funding. The founders of Low Impact Seismic Sources (LISS) were Steve and his son Jan, me, George Steel, and Claire Zopf. All we had was a patent application and the 2015 Seneca Lake LPS data to show. We needed modeling to show what the TPS would do. No commercial modeling program could model the low pressures and the large volumes of the TPS. At Stanford, Professor Eric Dunham was working on modeling volcanoes. I was also an adjunct professor at Stanford. I often saw Jon Claerbout and I told him about LISS. Jon told me “Airguns are like volcanoes” and took me to Eric’s office. Eric thought that the modeling was a good student-project. Soon afterwards Leighton Watson started a PhD under Eric. A few months later we had a program that could model LPS and TPS (Watson et al., 2016).

Robert Hobbs, another ex-Veritas person, joined LISS at the end of 2016. We went door to door in Houston seeking funding. Jay Hwang at Shell was interested to hear more. They were aware of the value of low-frequency signal. Based on their good experience with low-frequency Vibroseis in 2009, Fons ten Kroode et al. (2013) of Shell predicted that low-frequency signal was the future, and their data processing people were getting good results from what is usually called

full-waveform inversion. Tarantola (1984) supported this prediction. Shell brought up the TPS ambition level way beyond BLAST. The publication of Wolfspar (Dellinger, 2016) helped—we were not the only ones who believed in low frequency signal!

One concern was permitting. Robert and I went to talk to BOEM (the US Bureau of Ocean Energy Management) in Washington DC at the end of February 2018. We then had a video call with NMFS (National Marine Fisheries Service) in Florida. BOEM and NMFS were positive. They understood that the TPS was not just a giant airgun. They encouraged us to build one and acquire test data in quarries onshore. Then come back and show them data recorded with a small sampling interval. That is high-frequency data. We checked with NMFS that the high-frequency recorders that we were planning to use would be acceptable.

In March 2018 Shell contracted LISS to manufacture and test TPS. We opened a shop in Hillsboro, New Hampshire; hired Jan full time; and then hired another son, Fred. By the end of 2018 we started to have data from a quarry in Concord, New Hampshire. Towards the end of 2018 as we tested increasing volumes, we broke the TPS. On the positive side, the data was even better than promised. That is, the bubble period was longer than had been modeled. The best shot was the shot that broke the TPS which I called the Kamikaze Shot. Steve then designed a stronger TPS. The broken TPS became Mark 1, and the stronger design was named Mark 2. In 2019 we tested Mark 2 in a quarry in Virginia up to a volume of 20 thousand cui. In 2020, we tested it with a 26.5 thousand cui chamber first in a quarry and then offshore. It produced good data, and just as importantly, the crew (of the Sanco Atlantic) loved the TPS. BLAST no more. Sercel bought LISS 10 months after the offshore test.

This paper is about the TPS. First, how it is designed differently from airguns to have a lower environmental impact and produce a lower frequency signal. The paper is also about how it is deployed. It can be deployed in arrays, but it is better to deploy it as a single source. Data processing must adapt, and this paper also covers a process that we call joint designature, that is part of that adaptation.

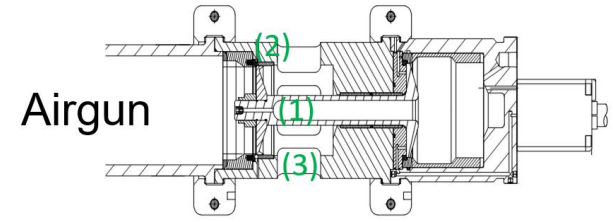
Materials and methods

Equipment

The TPS is a pneumatic source. Airguns are better known pneumatic sources, so a good way to describe the TPS is to compare it to an airgun. Airguns operate using air at 2000-2500 psi and their firing chambers have volumes of typically up to a few hundred cubic inches. In some cases, like in BLAST, they can have chambers of a few thousand cubic inches, but this can be problematic. The TPS operates using air at 600-1000 psi. It has firing chambers of tens of thousands of cubic inches. The TPS is not just a giant low-pressure airgun. It includes a few important differentiating design features that enable safe and environmentally friendly release of

such large amounts of air (figure 1). In figure 1 the firing chamber is on the left, the operating chamber is on the right, and the mid chamber is in the middle. The shuttle is composed of a shaft and two pistons. The firing piston on the left opens the ports and the operating piston on the right is on a bulkhead before triggering the source and moves into the operating chamber as the ports are being opened.

These design features make the TPS safer than airguns for the crew and they reduce the high-frequency content which makes it environmentally friendlier. The air-filled mid-chamber prevents cavitation and its associated high-frequency content. The zero-acceleration distance increases rise time and reduces the slope (figure 2). The slope is the first time derivative of the SPL. It is proportional to particle acceleration because sound pressure is proportional to the particle velocity. The proportionality constant is the acoustic impedance. A slope of 1 bar per millisecond means an acceleration of 7g, where g is 9.81 meters/sec^2. The slope of a single TPS is 1 bar.m/ms while the slope of a single airgun is 3 bar.m/ms. An array of 30 airguns all shooting simultaneously has a slope of 90 bar-meters/milliseconds vertically under the array. A creature swimming 90 meters under such an array will experience a slope of 1 bar.m/ms and therefore an acceleration of 7g which is uncomfortable if not damaging. In comparison, 90 meters away from a single TPS, the maximal particle acceleration is a harmless 78 milli-g.



Feature	Airgun	TPS	
Air fill/drain	via shuttle	direct	(1)
Flange	Flat piston	Cup-shaped	(2)
Acceleration distance	A few cm	Zero	(2)
Mid chamber	Water-filled	Air-filled	(3)

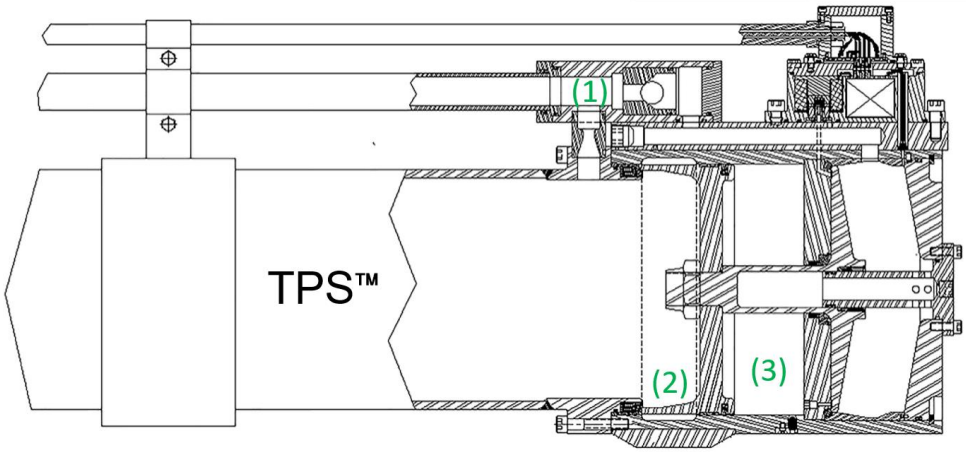


Figure 1: *Design features that are different between airguns and TPS. (1) The air draining method is directly from the firing and the operating chambers of the TPS with a check-valve that prevents auto-fires. The airgun method is via an orifice through the shuttle and because the pressure in the operating chamber drops before the pressure in the firing chamber, airguns often auto-fire when the air is drained. (2) The TPS has a cup-shaped flange and zero acceleration distance which increases the rise time. Airguns have flat firing pistons and non-zero acceleration*

distances which increase the slope and the high-frequency content. (3) The airgun's mid chamber is filled with water which causes cavitation when the water is venting while the shuttle is accelerating. The TPS' mid chamber is filled with air, which inhibits this cavitation.

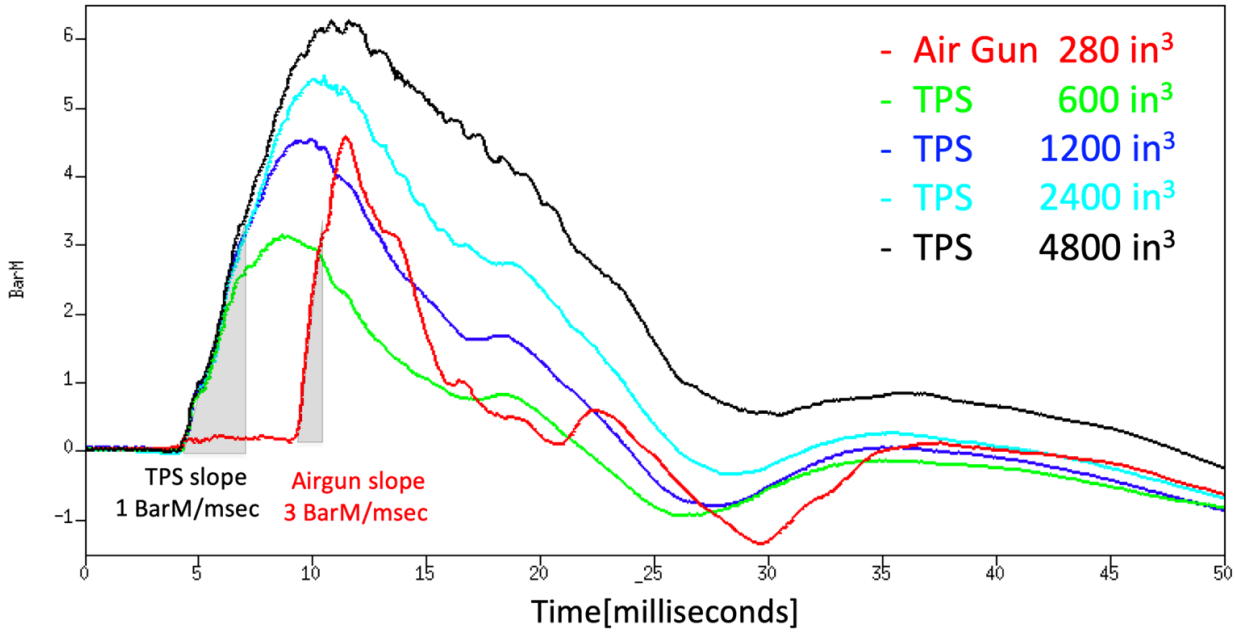


Figure 2. Source signatures of single TPSs with four different volumes and a single airgun. Note the difference in the slopes and the elimination of the time delay of 6 msec between triggering the airgun and opening its ports. The airguns have a so-called "shoulder" (Landrø, 2011) which the TPS does not have because it does not have an acceleration distance. With the TPS, the slope of the main peak is 1 bar-meter per millisecond, regardless of the volume. The slope of a single airgun is 3 bar-meter per millisecond.

Data acquisition method

The TPS has been tested on different surveys in the Gulf of Mexico, either deployed from booms under rigid floats or on a slip-way under a flexible float (figure 3). A still from an underwater video is shown in figure 4.

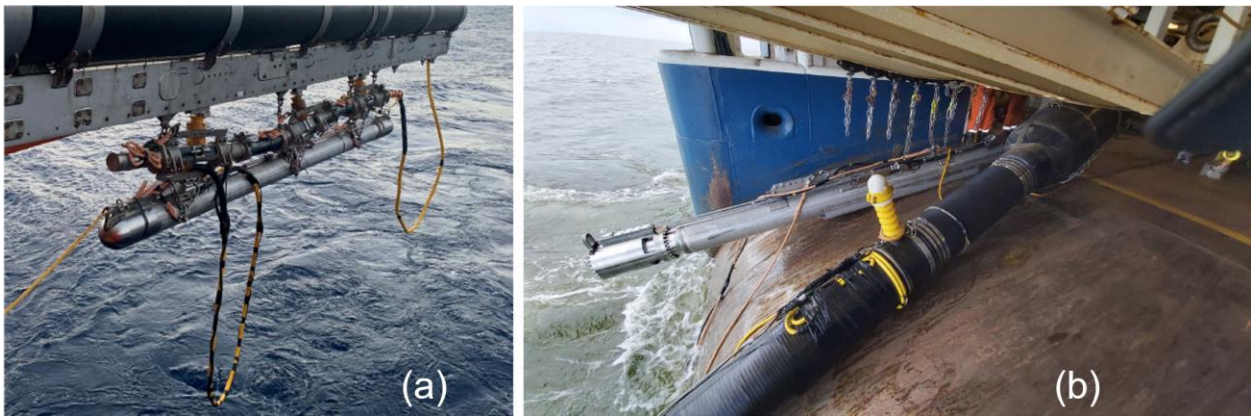


Figure 3. TPS deployed under a rigid float (a) on a slip-way with a flexible float (b). These pictures show the TPS with a 26.5 thousand cubic inch chamber.

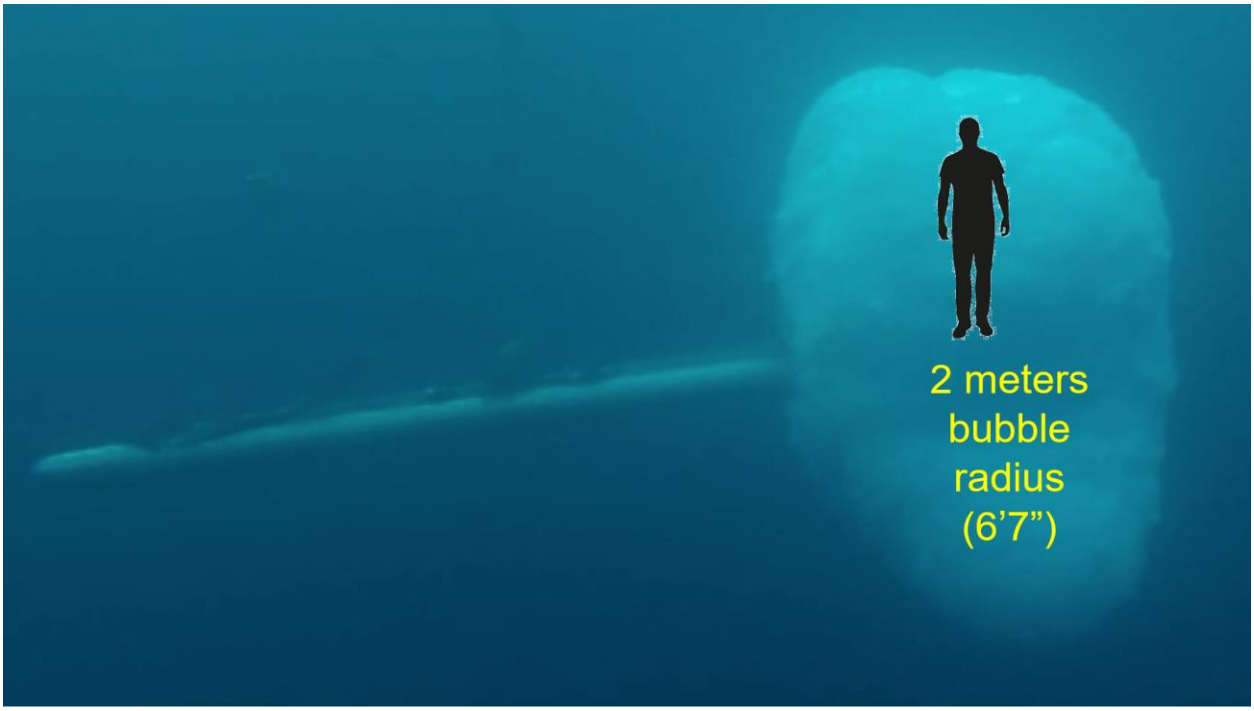


Figure 4. The bubble radius was 2 meters. The length of the TPS is 7.5 meters.

The data were recorded by ocean bottom nodes (OBN). The shots were up to 54 km offset from the furthest receiver. Conventional OBNs recorded data with a 2-millisecond sampling interval. The Nyquist frequency of such data is 250 Hz. Special OBNs recorded data with 10 microseconds. The Nyquist frequency of such data is 50 kHz. The special OBNs provided information on very high frequencies that are never used for seismic imaging but have an environmental impact.

Results

Geophysical value

Data from an array of conventional airguns and from a single TPS are shown in figures 5-8. Note the stronger and lower-frequency refractions from the TPS on the time-space domain (TX) data (figure 5). In the frequency (FX) domain (figure 6) note the lower frequency content of the signal with the TPS. Long-offset low-frequency (LOLF) data are shown in figure 7. The spectra are shown in figure 8.

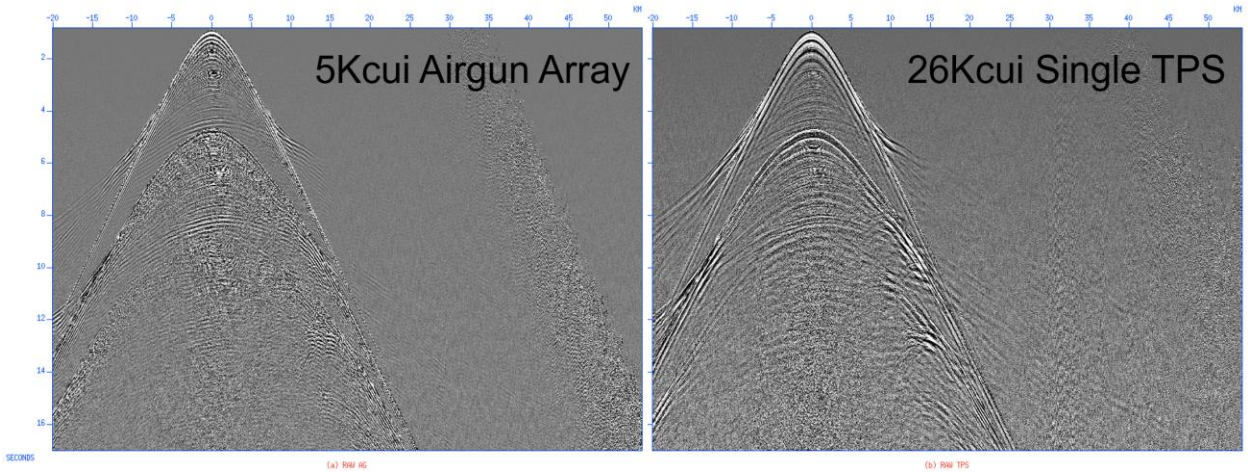


Figure 5. Common receiver gathers comparing data from an array of airguns whose total volume was 5110 cubic inch (left) to a single 26.5 thousand cubic inch TPS (right). Only spherical spreading gain was applied to the data.

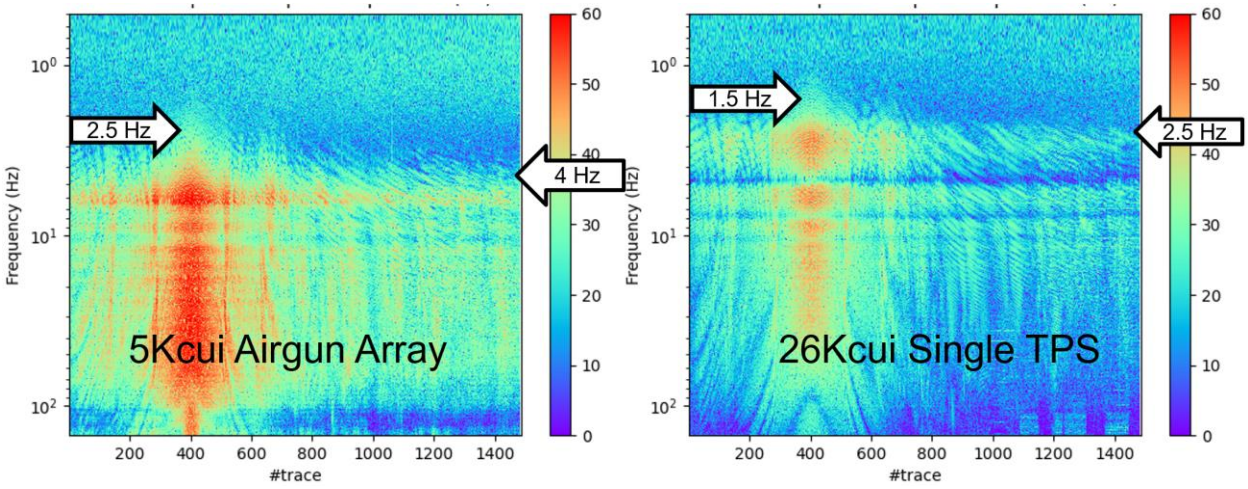


Figure 6. Spectra of the data in figure 5. Note the low-frequency limits annotated. TPS gains 1 Hz at zero offset and 1.5 Hz at an offset of 54 km. 1 and 1.5 Hz sound small. However, in octaves these are significant gains of 0.74 octaves and 0.68 octaves.

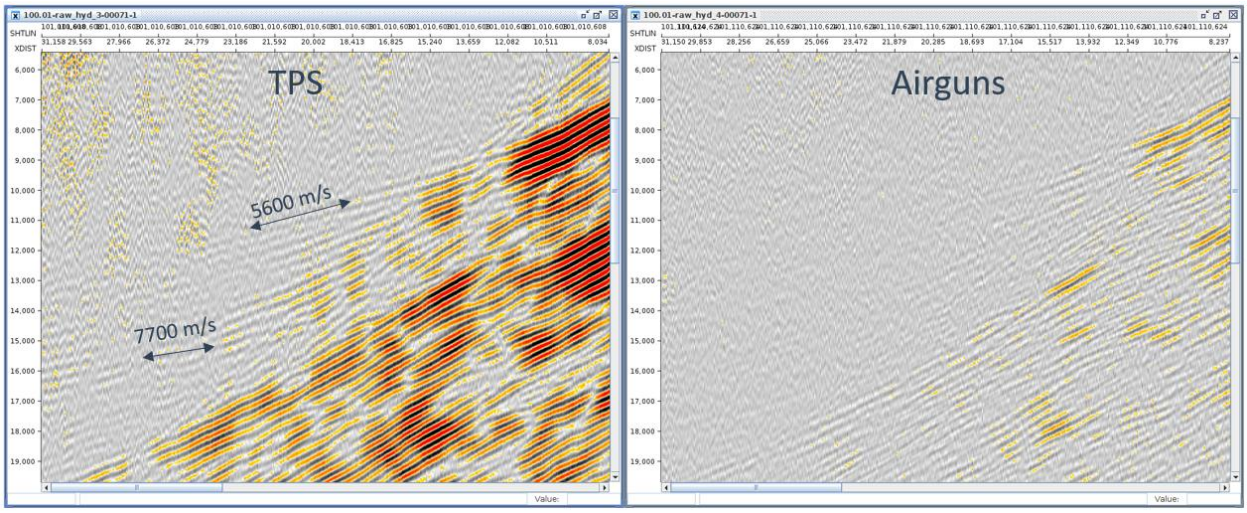


Figure 7. Far-offset data from TPS (left) and the production airguns (right). The data from salt area in the Gulf of Mexico were low-passed at 4 Hz. Note the higher low-frequency signal in the TPS. High velocity refractions and reflections are from the lower crust, sub-salt.

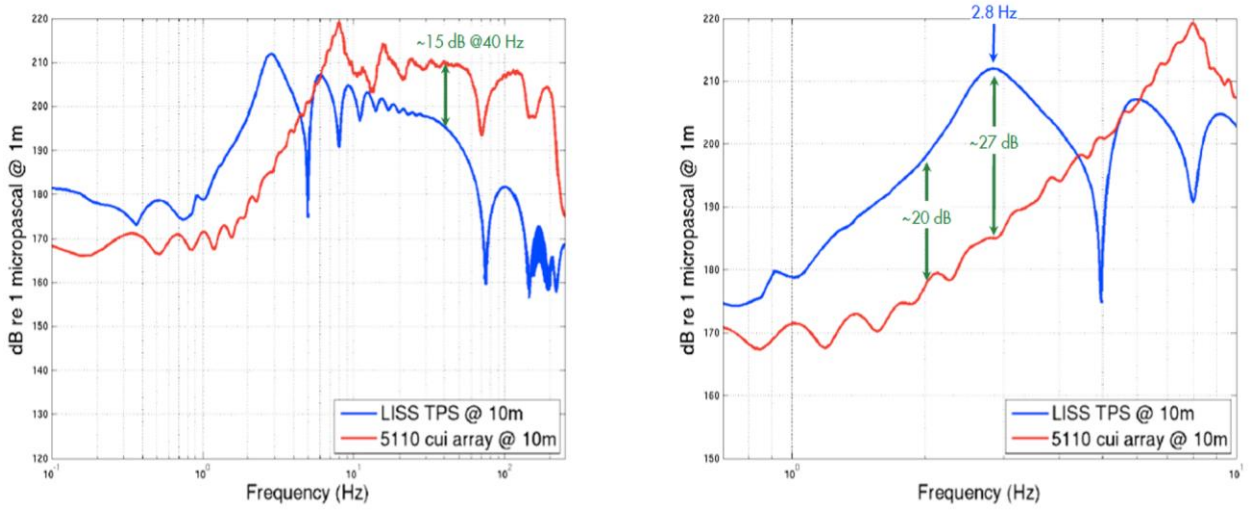


Figure 8. Spectra of TPS (blue) and Airguns (red). Note that the increase of low-frequency signal is 20-27 dB at 2-3 Hz. At 40 Hz, the TPS is 15 dB weaker than the array of airguns and it has a 40 dB deep trough at 4.9 Hz. The data are from an OBN with sampling interval of 2 millisecond hence Nyquist frequency 250 Hz.

Environmental impact

Figures 9-12 compare the environmental impact of TPS to that of an array of conventional airguns. Time-domain wavelets of airguns and TPS are overlaid on Figure 9. These are at zero offset, when the shots were above the node. Note that the airgun array's SPL is factor 13 larger than the TPS' zero-to-peak, and factor 18 larger peak-to-peak. The sound pressure level falls with offset. Figure 10 shows the SPL as a function of lateral offset between the shots and node. It is

about 10 dB in offsets that are longer than 5 km, and about 22 dB at zero offset, in agreement with a factor of 13 in figure 9,

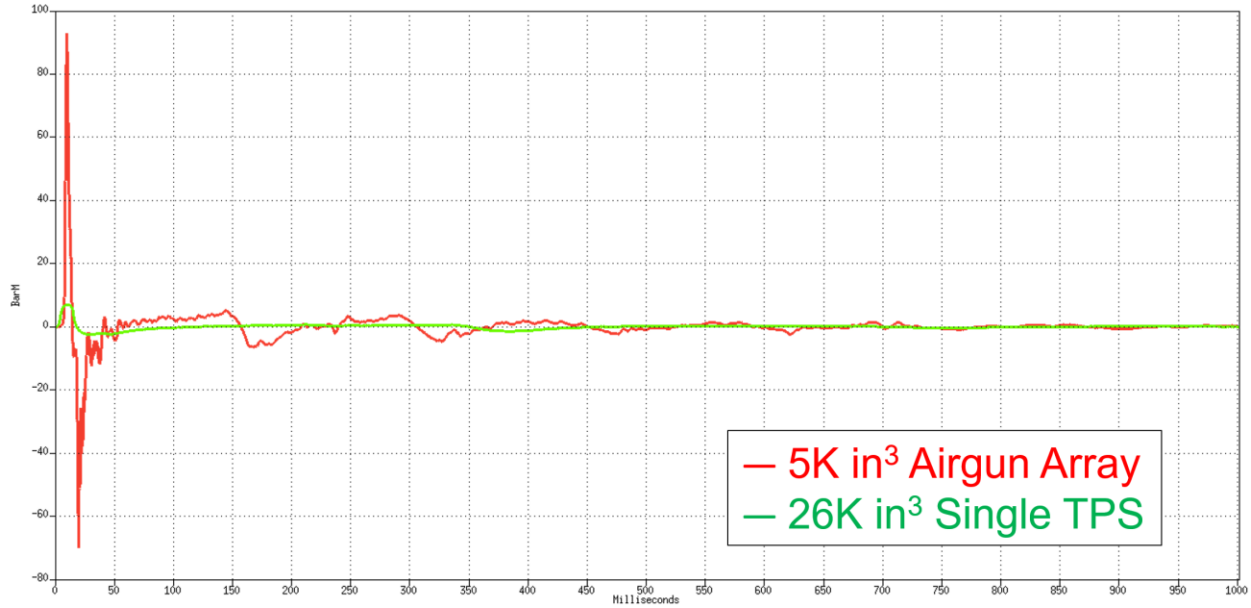


Figure 9. Wavelets of the airgun array in red and the TPS in green. Note that the zero-to-peak sound pressure level of the array of airguns at 92 bar-meter is 13 times (22 dB) higher than the TPS at 7 bar-meter. The difference between the peak-to-peak SPLs is much larger at 26 dB because the ghost of the TPS arrives while the air is still coming out of the ports. It does not make TPS deghosting more challenging. Just the look of the data makes people think there is a bias in the acquisition system.

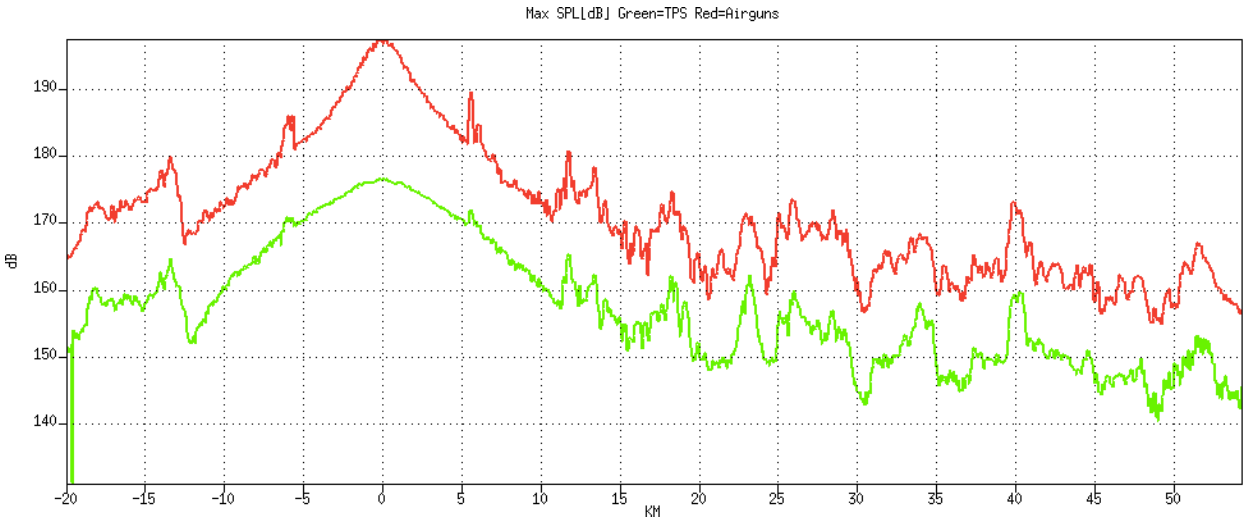


Figure 10. Maximal sound pressure levels. The TPS level in green is 10-20 dB lower than that of the Airguns.

Attention to duty cycles in marine acquisition is increasing because of the concern that non-impulsive sources such as marine Vibroseis might block communication between marine

mammals. Impulsive sources have lower duty cycles. However, their duty cycles are not negligible (figure 11).

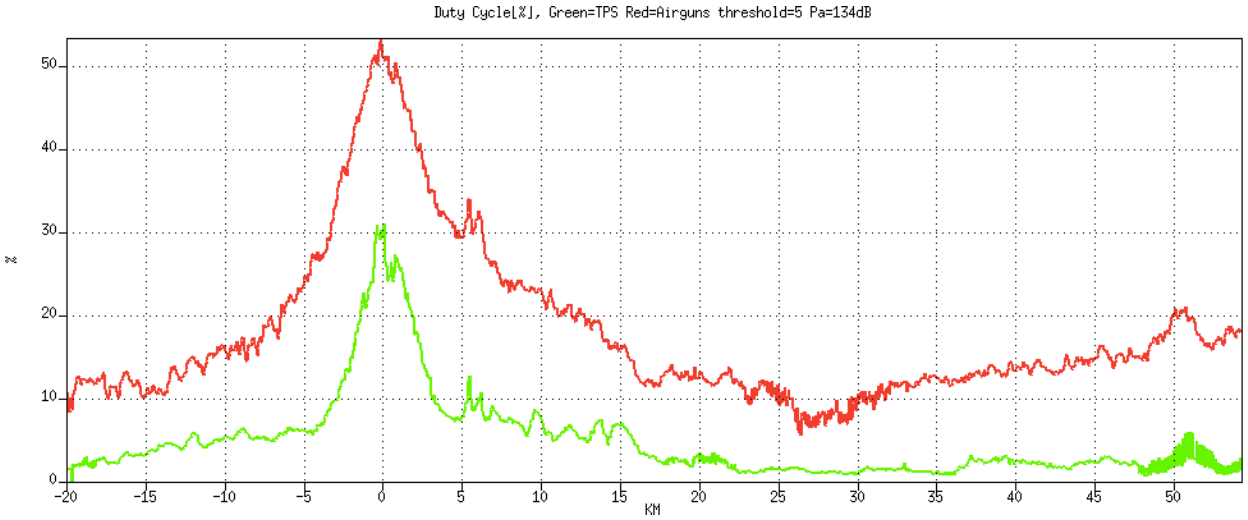


Figure 11. Duty cycle as a function of offset up to 54 km between the recording ocean bottom node and the source. TPS in green is much lower than the airguns. The duty cycle was calculated by counting the fraction of the time that the envelope of the data was above 5 Pa.

A special OBN recorded data at a sampling rate of 100 kHz, which is a 10-microsecond sampling interval, and 50 kHz Nyquist frequency. Figure 12 compares spectra of the two different active sources and noise from the continuous recording. 20 shots were averaged to reduce the instrument noise.

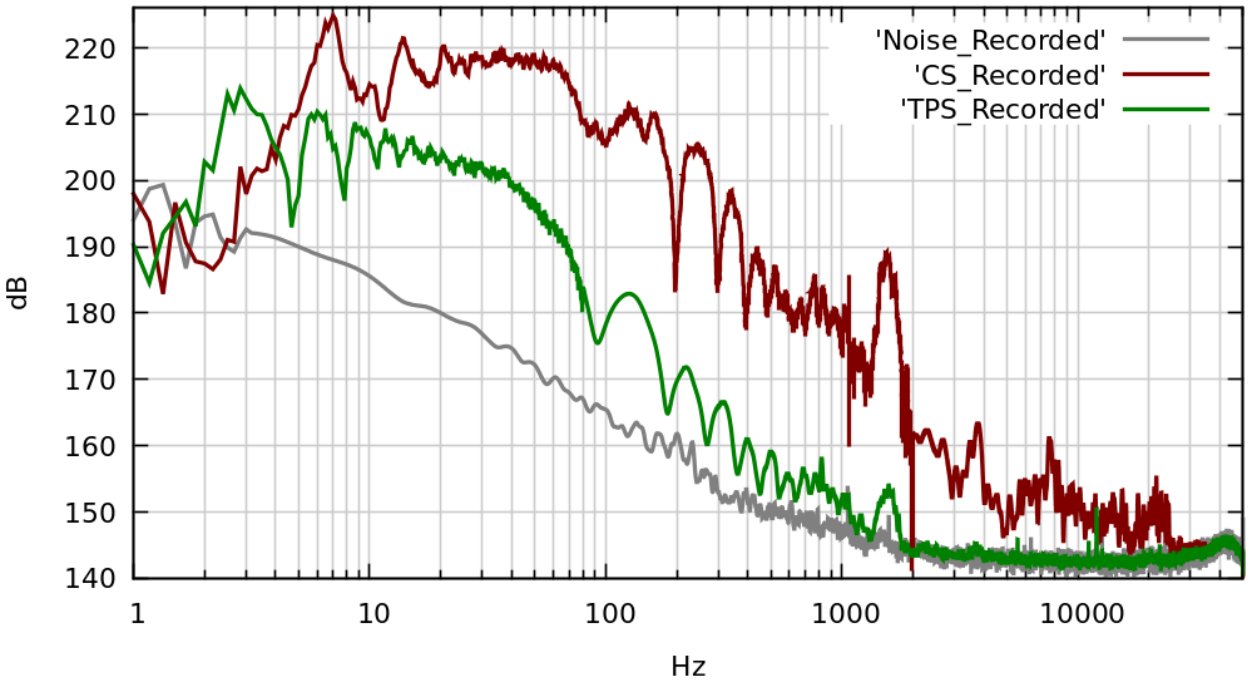


Figure 12. Spectra of TPS (green), airguns (red), and recorded noise (gray). The data are from a different survey than in figure 8. The measured increase in low-frequency signal for the TPS in this survey is 10-23 dB at 2-3 Hz. At 40 Hz, the TPS is 18 dB weaker than the array of

airguns and it has an 18 dB deep trough at 4.9 Hz. The data have an OBN sampling interval of 10 microseconds, hence the Nyquist frequency is 50 kHz. Significantly, the TPS does not emit waves above 1500 Hz, while the airgun upper limit is 25 kHz.

From source arrays to point sources

Twenty years ago, we used groups of receivers. Today, the industry is in transition to single sensors. On the receiver side, the transition to single sensors is complete onshore and on the seabed. On the source side, however, we are still using arrays of airguns (figure 13). Arrays made airguns similar to explosives because they maximized the peak sound pressure level with given compressor capacity. Unlike groups of receivers that are all the same, arrays of sources contain airguns of various sizes and therefore various voices. Arrays with variable-size airguns increased the peak-to-bubble ratio (PBR) because the main peaks were aligned, and the bubbles had a diversity of periods. PBR was paramount when the noisy recorders and the weak computers of the time limited the ability of data processing to designature the data. Now SNR is higher, and computers are faster, but we are still using heterogeneous arrays of many small airguns for historical reasons. It is time to move from airgun arrays to point sources. Point sources, like point receivers, provide more accurate timing (figure 14) and higher location accuracy. The directivity of point sources is simpler (figure 15). Modeling point sources is simpler and more reliable because there are no interactions between the sources in the array. Estimating far-field signatures from near-field hydrophone data is more reliable because there is no cross talk and there is no dependency on the position accuracy of the subarrays. Last but not least, single sources have better environmental effects (Abma 2018; Hegna et al., 2019). The maximum sound pressure level and the maximum slope of point sources is much lower, so their environmental impact is less.



Figure 13. Airgun array (left) and a point TPS (right). Note that the large number of interacting small bubbles of the array and the single large bubble of the TPS.

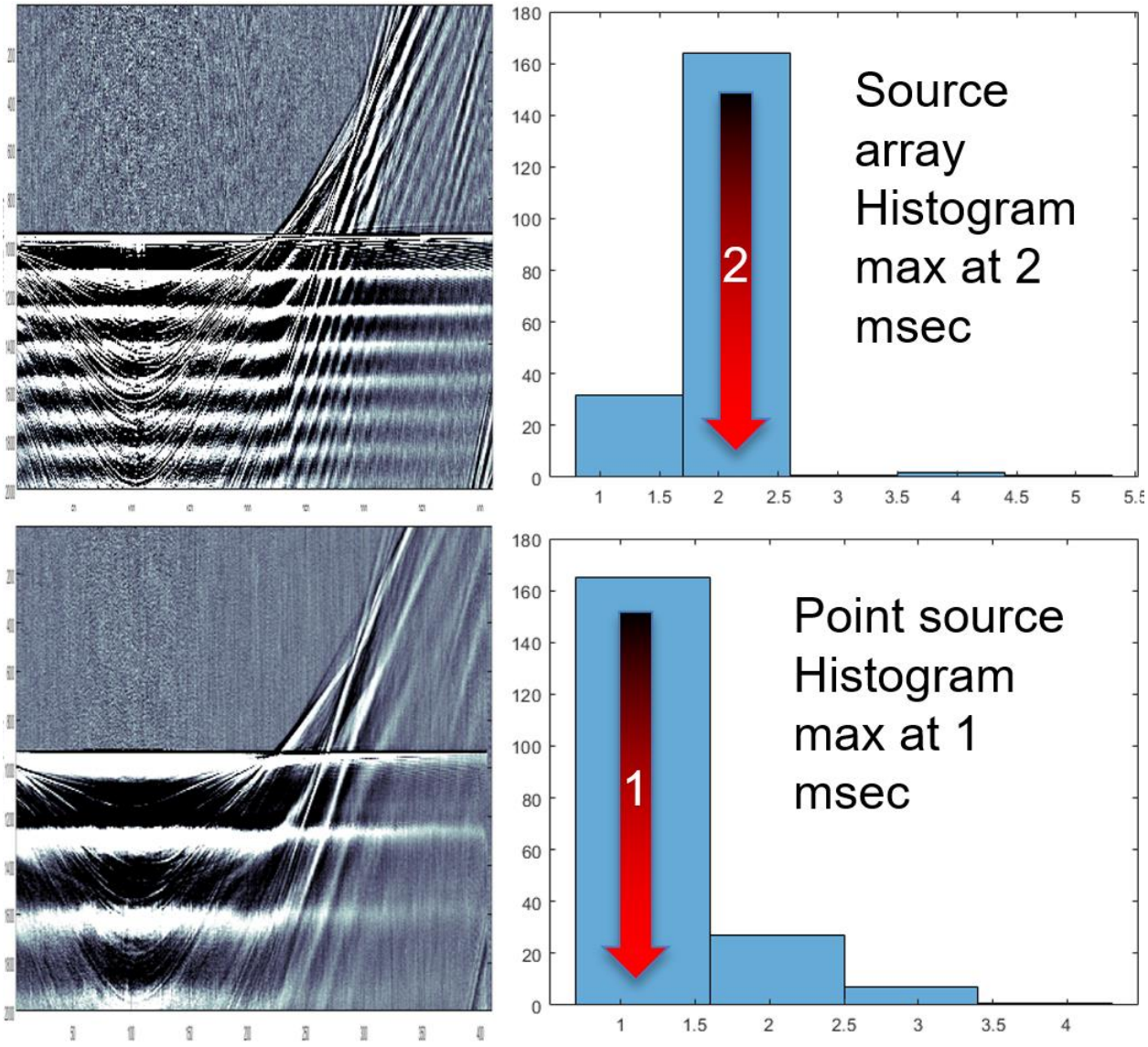


Figure 14. Timing accuracy of an airgun array (top) compared to a point TPS (bottom). The shot time QC is performed by picking the first break after hyperbolic moveout (HMO) static shifts that flatten the direct arrival. Data after HMO (left) and histogram of the time deviations (right).

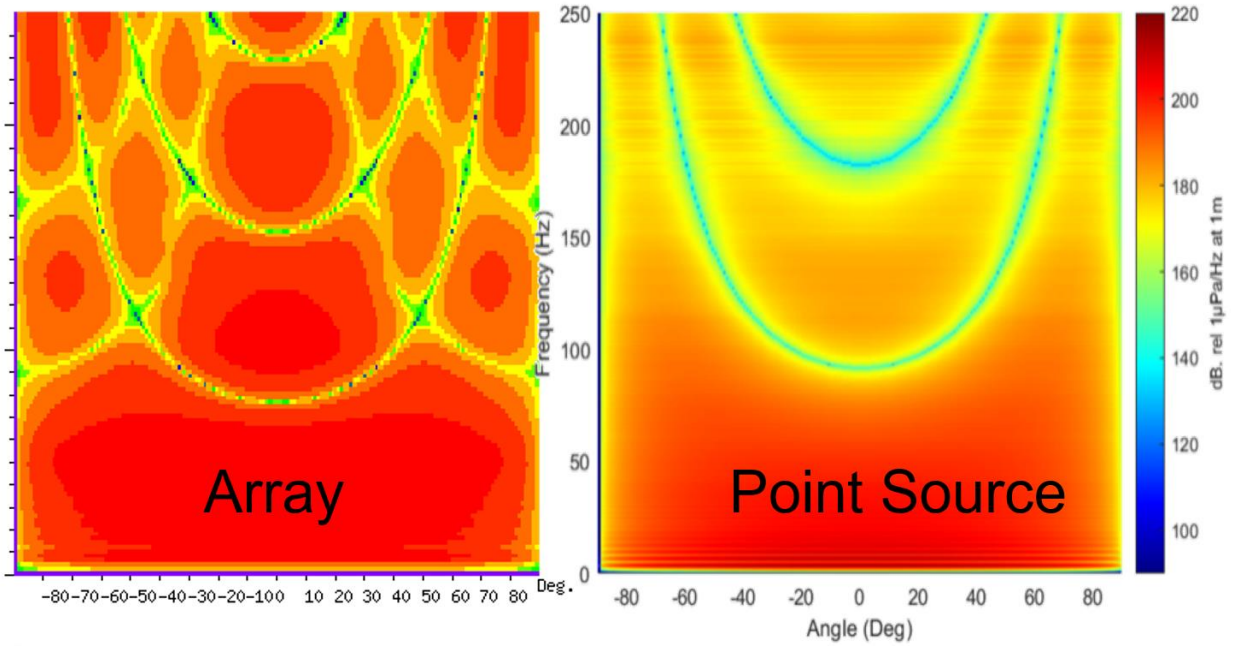


Figure 15. Source directivity spectra of an array (left) and a point TPS (right). The point source is much simpler because there is only the surface ghost while the array has the ghost and the sub-arrays.

There is also a practical reason to use point sources. Lower-frequency sources are larger. They require more air. High-frequency sources are smaller, they require less air, and they can be fired more often. High-frequency waves have shorter wavelengths, and they need to be sampled with shorter spatial intervals. Low-frequency sources cannot have short intervals with a limited compressor capacity. This is all good because the spatial sampling requirement and practical ability are in agreement. However, data processing must adapt to data with frequency-dependent shot intervals. Sparsely sampled low-frequency data must be interpolated to have the same locations, post interpolation, as the densely sampled high-frequency data. Shot interpolation is already performed to regularize dense but irregular OBN data. In addition to interpolation, different sources have different signatures. Joint designature (Ronen et al., 2022) includes digital array forming in the designature process. (Figures 16-21.)

Data = Convolution of Source Signature Wavelet and Reflectivity

$$D = W \cdot R$$

Designature:

$$R = \frac{W^* \cdot D}{|W|^2 + PWF}$$

PWF = Pre Whitening Factor prevents division by Zero

Joint Designature: Two wavelets, same reflectivity $D_i = W_i \cdot R \; ; \; i = 1,2$

$$\mathrm{R} = \frac{W_1^* \cdot D_1 + W_2^* \cdot D_2}{|W_1|^2 + |W_2|^2 + PWF}$$

Significantly: the zeroes of W_1 and W_2 are not co-located

Figure 16. The joint designature method.

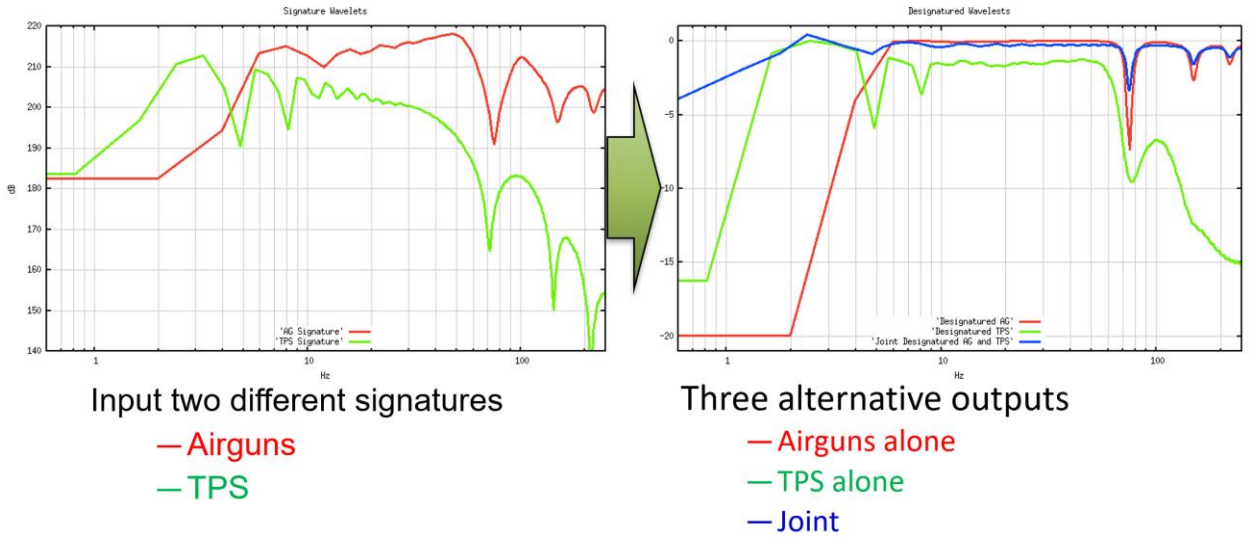


Figure 17. A 1D spectral illustration of joint designature. Input data (left): airguns in red and TPS in green. Three alternative outputs (right): Airguns designatured alone in red. TPS designatured alone in green. Joint designature in blue.

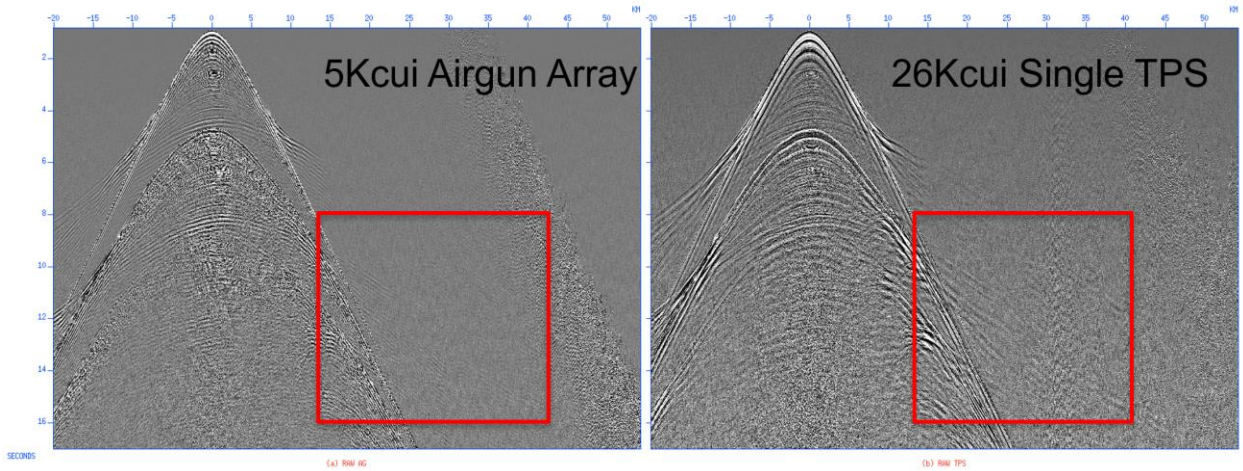


Figure 18. Data selected to demonstrate joint designature. Input airgun data (left) and TPS data (right). Data in the boxes are shown in figure 20.

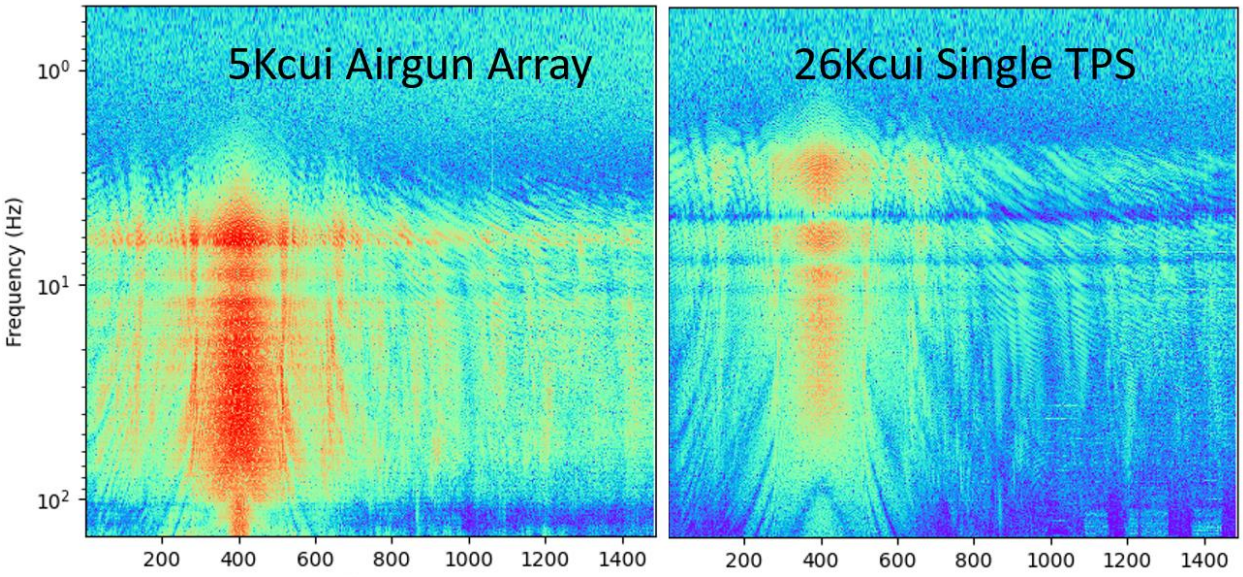


Figure 19. F-X Spectra of TPS (right) and airguns (left). Note the significantly stronger low-frequency content of the TPS.

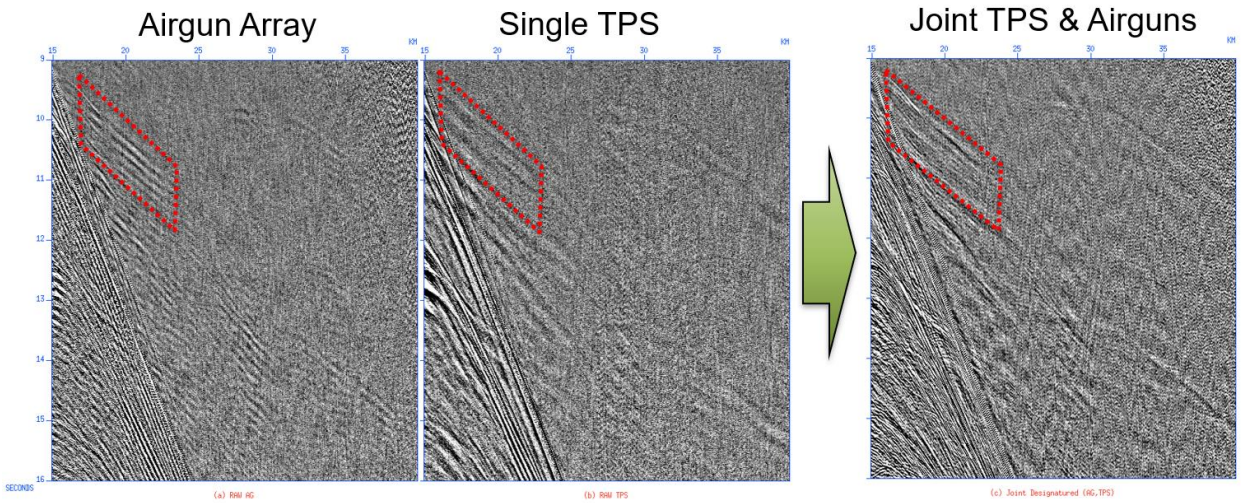


Figure 20. Input airgun data (left). Input TPS data (center). Output joint designature (right). Note that the airgun and TPS bubbles (red box) were turned from noise to signal by the joint designature.

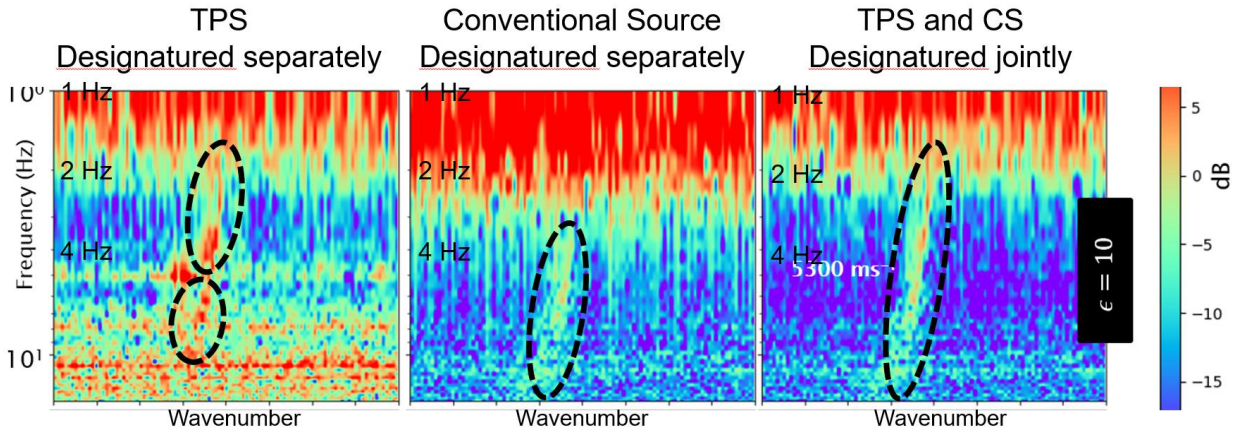


Figure 21. F-K Spectra of TPS designatured alone (left). Conventional source (airguns) designatured alone (center). Joint designature (right).

Conclusions

The Tuned Pulse Source evolved from airguns. Yet, it is a new species of source, with a lower environmental impact and more low-frequency signal. The TPS will be deployed as point sources rather than in arrays and its data processing will include joint designature.

References

Abma, R., 2018. Shot coding design for popcorn shooting. SEG conference. Expanded abstract. DOI: https://doi.org/10.1190/segam2018-2995736.1

Berg, E., Svenning, B., and Martin, J., 1994. SUMIC: A new strategic tool for exploration and reservoir mapping: 56th Conference and Exhibition, EAGE, Extended Abstracts, 477–480

Chelminski, S. 1966. Acoustic wave impulse generator repeater. US patent 3249177.

Coste, E., Gerez, D., Groenaas, H., Larsen, O.P., Wolfstirn, M., Hopperstad, J-F., Laws, R., Norton, J., and Padula, M., 2014. Attenuated high-frequency emission from a new design of air-gun. SEG Technical Program Expanded Abstracts. DOI: https://doi.org/10.1190/segam2014-0445.1

Dragoset, W.H., 1988. Processing for seismic data from slanted cable. US Patent 4,992,992.

Dellinger J, Ross, A., Meaux, D., Brenders, A., Gesoff, G., , Etgen, J., , Naranjo, J., Openshaw, G., and Harper, M., 2016. Wolfspar ®, an "FWI friendly" ultralow frequency marine seismic source. SEG 2016. DOI:10.1190/SEGAM2016-13762702.1

Hegna, S., Kl¨uver, T., Lima, J., and Wisløff, J-F., 2019. Making the transition from discrete shot records to continuous seismic records and source wavefields, and its potential impact on survey efficiency and environmental footprint. Geophysical Prospecting, 2019, 67, 1472–1485. URL: https://www.pgs.com/marine-acquisition/tools-and-techniques/eseismic/

Landrø, M., Amundsen, L. and Barker, D. [2011] High-frequency signals from air-gun arrays. Geophysics, **76**, no. 4, Q19–Q27, DOI: http://dx.doi.org/10.1190/1.3590215.

Ronen, S. and Chelminski, S. [2017] Tuned Pulse Source - a new low frequency seismic source. 87th SEG Conference and Exhibition, expanded abstract. DOI: https://doi.org/10.1190/segam2017-w16-04.1

Ronen, S., Allemand, T., Laroche, S., Herrmann, P., Macintyre, H., Kryvohuz, M., and Baetan, G., 2022, Joint Designature of data with a diversity of sources. DOI: https://doi.org/10.1190/image2022-3746507.1

Strandenes, S., Vaage, S., and Sodun, A., 1991. "Comparison of Air-gun Clusters. *SEG Expanded Abstract,* 10., pp792-795.

Tarantola, A. ,1984, Inversion of seismic reflection data in the acoustic approximation. Geophysics, **49(8)**, 1259–1266. DOI: https://doi.org/10.1190/1.1441754

Tellier, N., Large, J., Ronen, S., and Aznar, J., 2021. A new wave in marine seismic source technology. First Break, volume 39, issue 11, p 89-95. DOI: https://doi.org/10.3997/1365-2397.fb2021088.

Tenghamn, R. and Dhelie, P., 2009. GeoStreamer – increasing the signal-to-noise ratio using a dual-sensor towed streamer. First Break **27**, pp.45-51. DOI: https://doi.org/10.3997/1365-2397.2009017.

Tegland, E.R., 1977. 3-D seismic techniques boost field development. Oil and gas journal, **75**, pp 79-82.

Ten Kroode, F., Bergler, S., Corsten, C., De Maag, J., Strijbos, F. and Tijhof, H., 2013. Broadband seismic data -The importance of low frequencies. Geophysics, Vol. **78** No.2, pp. WA3–WA1. DOI: https://doi.org/10.1190/geo2012-0294.1

Threadgold, I.M., Zembeck-England, K., Aas, P-G., Fontana, P.M., Hite, D., and Boone, W.E., Implementing a Wide Azimuth Towed Streamer Field Trial: The What, Why and Mostly How of WATS in Southern Green Canyon. SEG 2006. DOI: https://doi.org/10.1190/1.2370129

Watson, L., Dunham, E., and Ronen, S., 2016. Numerical modeling of seismic Airguns and low-pressure sources. SEG 2016. DOI: https://doi.org/10.1190/segam2016-13846118.1

Ziolkowski, A., Parkes, G., Hatton, L., and Haugland, T., 1982. The Signature of An Air Gun Array: Computation from Near-Field Measurements Including Interactions," *Geophysics,* Vol 47, pp1413-1421.

Ziolkowski, A., Hanssen, P., Gatliff, R., Jakubowicz, H., Dobson, A., Hampson, G., Li, X-Y., and Liu, E., 2003. Use of low frequencies for sub-basalt imaging. Geophysical Prospecting, **51**, pp. 169-182. DOI: https://doi.org/10.1046/j.1365-2478.2003.00363.x

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